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Special Report 81-2

March 1981

LEVEL II

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METHOD FOR COINCIDENTALLY DETERMINING SOIL HYDRAULIC CONDUCTIVITY AND MOISTURE RETENTION CHARACTERISTICS

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Prepared for
OFFICE OF THE CHIEF OF ENGINEERS
By
UNITED STATES ARMY
CORPS OF ENGINEERS
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
HANOVER, NEW HAMPSHIRE, U.S.A.

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: Special Report 81-2	2. GOVT ACCESSION NO.: AD-A099136
3. RECIPIENT'S CATALOG NUMBER: 14	
4. TITLE (and Subtitle): METHOD FOR COINCIDENTALLY DETERMINING SOIL HYDRAULIC CONDUCTIVITY AND MOISTURE RETENTION CHARACTERISTICS,	5. TYPE OF REPORT & PERIOD COVERED: CRREL-SR-81-2
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): Jonathan Ingersoll	8. CONTRACT OR GRANT NUMBER(s): FHWA 5-3-0202 and FAA DOT-FATQWA-707
9. PERFORMING ORGANIZATION NAME AND ADDRESS: U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire 03755	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: CWIS 31284
11. CONTROLLING OFFICE NAME AND ADDRESS: Office of the Chief of Engineers, Washington, D.C. 20314	12. REPORT DATE: Mar [redacted] 81
	13. NUMBER OF PAGES: 13
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Hydraulic conductivity
Soils
Soil tests
Soil mechanics

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A constant-head permeameter has been modified to include the essential components of a Tempe cell moisture extractor. With this equipment, tests for saturated hydraulic conductivity (permeability), unsaturated hydraulic conductivity and moisture retention characteristics of the soil can be conducted using the same soil sample. The procedure can be used for both absorption and desorption phases.

Test results from four different soils (a glacial till, a fine sand, a silt and a coarse sand) are presented. The effects of density on hydraulic conductivity

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20. Abstract (cont'd)

and moisture retention characteristics are shown.

PREFACE

This report was prepared by Jonathan Ingersoll, Civil Engineering Technician, Geotechnical Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. The study was funded under Chief of Engineers Civil Works Project CWIS 31284, Crop Management Aspects of On-Land Utilization of Wastewater; Program, Wastewater Management; Research Subprogram, Land Treatment; Federal Highway Administration Order 5-3-0202, Development of Mathematical Model to Correlate Observed Frost Heave of Highway and Airport Pavements with Laboratory Predictions; Federal Aviation Administration Order DOT-FATQWA-707, Ground Conductivity and Wave Tilt Measurements.

This report was technically reviewed by Dr. Richard Berg of CRREL, and Dr. Gary Guymon of the University of California at Irvine. The suggestions and comments of both these individuals made a valuable contribution to this manuscript. Discussions with Dr. James N. Luthin, University of California at Davis, were invaluable during the development of the procedures and equipment reported here.

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METHOD FOR COINCIDENTALLY DETERMINING
SOIL HYDRAULIC CONDUCTIVITY AND MOISTURE RETENTION
CHARACTERISTICS

Jonathan E. Ingersoll

INTRODUCTION

Frost heave occurs when sufficient migrating soil water reaches a freezing soil zone. Water is drawn to this zone by tension (or suction) created during the freezing process. The ability of water to flow through soil governs the rate and severity of heaving and influences the amount and duration of thaw weakening.

In wastewater spray irrigation systems, the efficiency of pollutant removal depends primarily on the ability of the water to permeate the soil at an optimum rate. Over-application can cause undesired overland flow of pollutants, while under-application reduces efficiency. When unsaturated hydraulic conductivity values are known, the optimum rate of application can be calculated and application can be adjusted to fall within specified limits.

In both of these cases it would be helpful to know the hydraulic conductivity and moisture retention characteristics of the soils. The purpose of this report is to describe a procedure that allows these characteristics to be determined using the same soil sample throughout the test. The test method is a modified version of unsaturated hydraulic conductivity tests described by Klute (1965) and Fukuda and Luthin (1980). The description of the apparatus and procedure is not presented in great detail, as the test is still in the development stage and the permeameter apparatus was mostly improvised from existing laboratory equipment.

MOISTURE CHARACTERISTICS

Capillary forces and adsorption forces within the soil create intergranular stresses (called soil tension or soil moisture stress) that vary during the wetting and drying processes. Tension is measured with a tensiometer (Fig. 1), which consists of a saturated porous cup connected to a vacuum gauge manometer or pressure transducer by a water-filled, flexible plastic tube. When the porous cup is inserted in the soil, it comes in contact with the soil water and transmits the tension through the tube to the measuring device.

When the change in soil tension with soil depth is known for a given field situation, the gradient of soil moisture with depth can be determined from a moisture retention characteristic curve worked out in the laboratry using the method described in this report. When the soil moisture gradient is known, the unsaturated hydraulic conductivity can be determined, again by referring to a curve worked out in the laboratory using the method de-

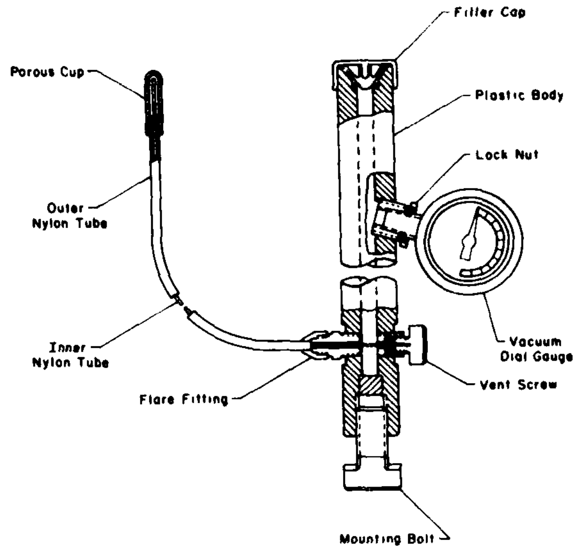


Figure 1. Tensiometer (manufactured by Soilmoisture Equipment Corp., Model 2100).

scribed below. The rate of water flux between two soil depths can be computed if the unsaturated hydraulic conductivity at those depths is known. It is important that the soil tension and conductivity be known because the rate of water flux through a relatively dry soil can be five or six orders of magnitude less than flow through a saturated soil.

EQUIPMENT

To test a soil for its hydraulic conductivity and moisture retention characteristics, a soil sample is placed in a cylinder similar to that used for a constant-head permeability test (Lambe 1951). The cylinder I used was made from clear plastic stock with a 3.0 in. (7.62 cm) inside diameter. It was cut to a length of 4.0 in. (10.16 cm).

Both the top and bottom caps of the cylinder contain a porous stone (Fig. 2). These stones have characteristic air entry values (AEV's) which are measures of the air pressure necessary to force water from their pores when they are saturated. The stones must have AEV's greater than the pressures to be administered during the test. The end caps and porous stones I used were taken from the base plates of large Tempe cells used for moisture retention testing. These cells were obtained from Soilmoisture Equipment Corporation of Santa Barbara, California.

A constant-head water supply is connected to the top cap through a three-way valve. The bottom cap has an outflow port connected to another three-way valve. Water flows out through the bottom valve to a volumetric flask. Both end caps must make an airtight seal with the cylinder.

Two porous ceramic cups, also with sufficient AEV's, are implanted in the soil through holes in the cylinder wall, one 6 cm above the other. (I used spare tensiometer cups, which can also be obtained from Soilmoisture

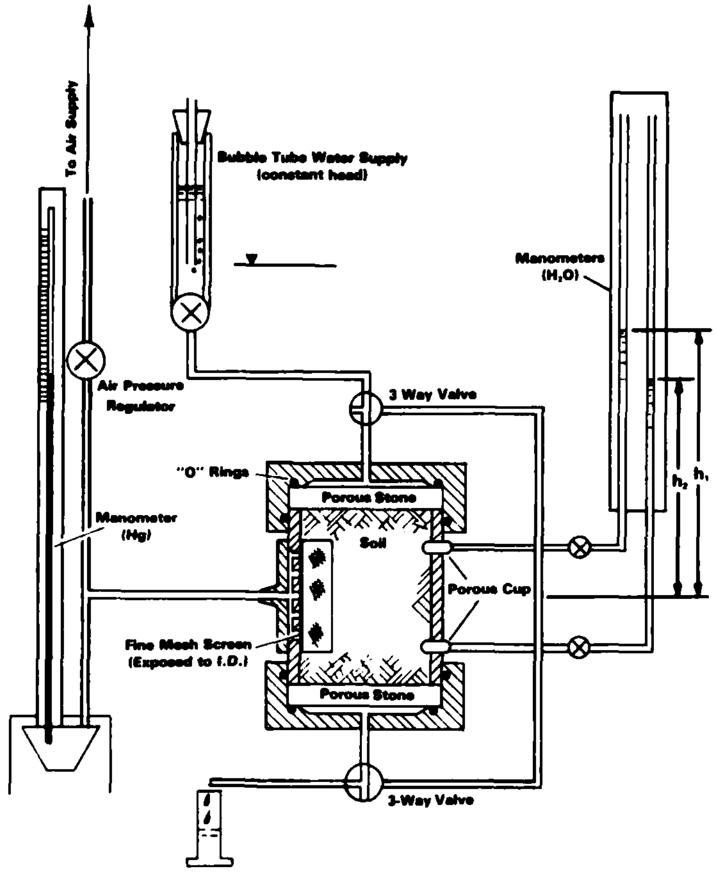


Figure 2. Pressure cell permeameter.

Equipment Corporation.) Each ceramic cup is connected to a water manometer. The manometers measure the head loss between these points. The distance between the cups is the length L of the sample.

Air pressure can be applied to the soil within the cylinder through several small holes, each about 1 mm in diameter, drilled through the cylinder wall (Fig. 2). A fine-mesh (#200) screen placed between the soil and the cylinder wall contains the soil. Grooves etched on the outer surface of the cylinder between the holes disperse the air evenly to all the holes. The holes are covered by a clear plastic cylinder segment having the same inside diameter as the outside diameter of the soil cylinder. The edges of the segment are sealed to the cylinder with epoxy. A hole is drilled through the outer segment and a hose connector is cemented in place. An air pressure regulator and a mercury manometer connected to the segment complete the pressurizing equipment.

A tube connects the top and bottom three-way valves, by-passing the soil cylinder. This connection enables the pore water to flow through the top and bottom porous plates simultaneously when pressure is applied, reducing the time for it to reach equilibrium.

SAMPLE PREPARATION

The soil to be tested is first wetted slightly to make it sufficiently cohesive to remain in the cylinder during molding. The soil is placed in the cell in several layers and tamped to a density approximating that of the soil in the field. The surface of each layer is scarified to improve soil pore continuity. Compacting the soil is difficult, as the porous cups in the cylinder wall are fragile. (I sealed the cups in place before molding; however, they could be inserted later if a method of sealing following molding can be devised.) When the cylinder is filled with soil, the ends are trimmed square, and the cylinder and soil are weighed. The wet and dry densities are then calculated.

After the soil is in the cylinder, the end caps are placed on the top and bottom. The stones in the caps must be kept as dry as possible, as air cannot escape once the pores are saturated. For the same reason, the soil must be wetted only slightly.

The assembled cylinder is placed in a vacuum jar and evacuated for four hours. While still under a vacuum, de-aired water is allowed to rise slowly within the jar until the top cap is immersed. This process evacuates air from the soil, stones and cups, allowing unrestricted water movement through all the components and saturating the stones, cups and soil simultaneously.

When the saturation process is complete, the cylinder is connected to the remaining components. All valves and tubing are filled with water. Extreme care must be taken to keep air out of the system when connecting the tubing and valves; an air lock can easily block water flow, especially in the valves.

If desired, undisturbed soil samples could be placed in the cylinder and tested in the same manner. Obviously, the porous manometer cups would have to be inserted after a sample is in place. Also, the diameter of the sample would have to coincide with the test cell, or if the diameter of the soil core is slightly less than the cylinder, paraffin could be poured in to fill the voids. (I have not yet used this procedure.)

The manometers used for measuring head loss should be thoroughly cleaned and calibrated before starting a run, especially when sand or other highly pervious soils are being tested. As conductivity calculations only require a head <u>loss</u>, calibration can be made by attaching a common head to the tubes simultaneously. The common head should be raised to several positions. Ideally, the two manometers will coincide; however, if the diameters of the capillary tubes vary, there will be a slight difference in the heights of the water columns. Uncleaned tubes will also affect the heights. The corrections determined here should be applied to the head loss measurements during a test.

When running hydraulic conductivity tests near saturation, the restricted water flow through the end caps lowers the head loss (frequently to the 1- to 5-mm range). As the test progresses to drier conditions, the head loss can range from 30 to 50 cm, making the capillary tube error less important.

TEST PROCEDURE

The first step in the test procedure is to saturate the soil in a vacuum. This is followed by a conventional saturated hydraulic conductivity (permeability) test, where a measured quantity of water flows through a soil column in a known time at atmospheric pressure. The three-way valves are set to allow water to flow from the water supply through the soil, and into the collecting flask. Hydraulic conductivity k is calculated using

$$k = \frac{QL}{dAt}$$

where: k = hydraulic conductivity (cm^3 per unit time)
Q = quantity of water (cm^3)
A = sample area (cm^2)
L = length (cm)
t = time
d = head loss (cm).

When this test is completed, the three-way valves are turned to allow water to flow simultaneously through the top and bottom plates into the discharge tube.

The unsaturated hydraulic conductivity test begins by applying the first increment of air pressure, say 3 kPa (30.6 cm H_2O). All the water that is expelled from the discharge tube is collected. When flow stops and equilibrium has been reached, the quantity of extracted water is recorded. This quantity will be used for developing the moisture retention curve.

To calculate the mean cell pressure $\bar{p}$ for any hydraulic conductivity value, use this equation:

$$\bar{p} = P + h_1 + h_2$$

where P is the amount of air pressure applied (in cm of H_2O) and h_1 and h_2 are the distances (in cm) from the midpoint between the porous cups of the water manometers to the top and bottom menisci, respectively. (The results can be converted from cm of H_2O to kPa by multiplying by 0.098.)

After the first increment of air pressure has been applied, water has been extracted from the larger pores. The smaller pores are still filled or partially filled with water. These smaller pores will allow water to flow through the sample, but at a reduced rate.

A second hydraulic conductivity test is then run. The air pressure applied to the soil is kept at 3 kPa (30.6 cm of H_2O). The three-way valves are set to allow water to flow through the soil from the water supply. The volumes of water going into and coming out of the soil are monitored until they become equal. The water manometers used to measure the head loss are allowed to stabilize. After equilibrium is reached, the quantity of outflow is recorded for a measured period of time and the hydraulic conductivity is computed as before.

It is important to record carefully all water intake and outflow throughout the test. The total intake usually is somewhat greater than the outflow, especially following low pressure extraction. This is probably caused by a rearrangement of the meniscus configuration when the water starts to flow during the conductivity test. Also, it is necessary to have the rate of intake the same as outflow (showing that equilibrium has been reached) before the test can be conducted. The manometers must reach equilibrium as well.

As with most permeability test procedures, a constant temperature is important. This becomes critical when testing the low permeability ranges, as liquid expansion and contraction can influence the results.

The procedure described above is repeated for as many pressure increments as desired. When the final hydraulic conductivity increment has been completed, all valves are turned to prevent water from entering the system when the internal pressure is released. The soil is then removed from the cylinder and the moisture content is determined.

The amounts of water extracted during each increment are added to this final value. From these totals, water content can be calculated for each pressure increment and a plot can be constructed of the percentage of water (by weight or volume) vs pressure (kPa).

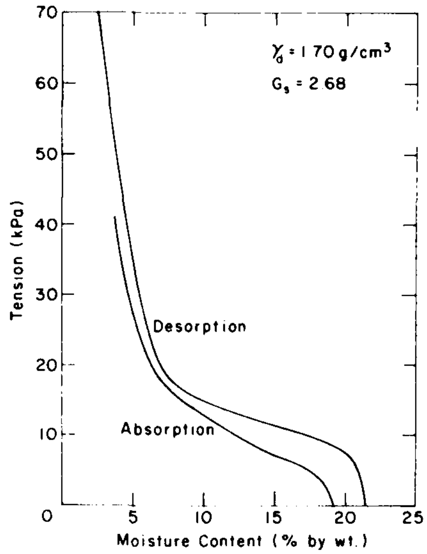
It is generally accepted that air pressure against the soil surface produces the same effect as tension or suction through the soil base. In view of this, a second plot can be constructed using tension (kPa) vs hydraulic conductivity k. With these two plots, unsaturated hydraulic conductivity can be found for the range of water content covered during the tests. Hydraulic conductivity values will drop from 3 to 6 orders of magnitude as pressures increase towards 100 kPa (1 bar). I have also found it beneficial to plot degree of saturation vs hydraulic conductivity.

It is helpful to calculate continuously the volume of water remaining in the soil from the start of the test. Ideally, this procedure is quite accurate, especially if the soil is vacuum-saturated at the outset. Realistically, however, water content values are more accurate when they are calculated from the final water content.

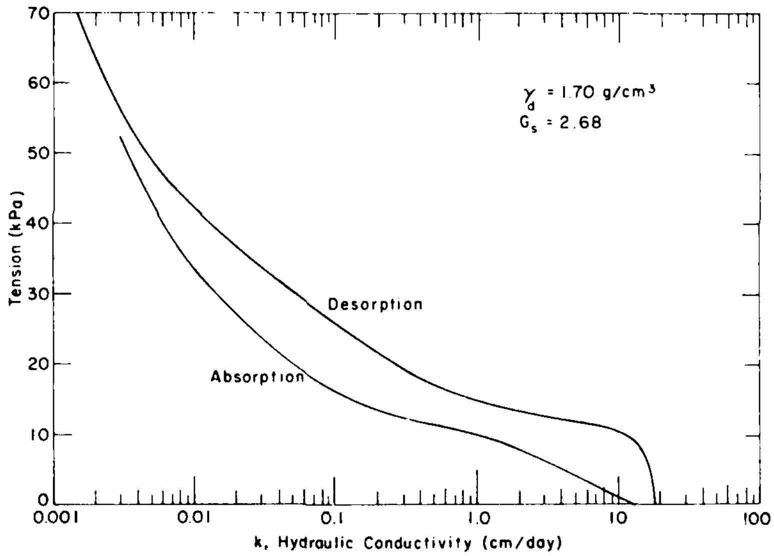
To follow the changes in water content of a vacuum-saturated sample, the total void volume must be calculated. For this, the specific gravity of the soil and the bulk dry density are needed. First determine the porosity n from

$$n = 1 - \frac{\gamma_d}{G_s}$$

where γ_d is the dry density (g/cm^3) and G_s is the specific gravity of solids.



a. Moisture retention.



b. Hydraulic conductivity.

Figure 3. Hysteresis that occurs with absorption and desorption curves for Ikelanian sandy silt.

The total void volume V_{vt} is

$$V_{vt} = n \cdot V$$

where V is the total sample volume (cm^3).

This total void volume equals the volume of water contained in the soil at the start of the test. Volumetric and gravimetric water contents are calculated throughout the test by deducting the volume of water extracted during each pressure increment.

After completing the test procedures described above, I allowed water to re-enter the soil incrementally by reducing the pressure. The only change from the original procedure was to lower the water source during water uptake to the elevation of the center of the sample. Following each change in pressure, water uptake was recorded and hydraulic conductivity determined. The results of this technique for a sandy silt are shown in Figures 3a and b. A significant hysteresis occurs between the absorption and desorption stages in the moisture retention and hydraulic conductivity curves for most soils.

RESULTS FROM FOUR SOIL TYPES

I tested this technique with many soils, including the following:

1. Chena silt, a non-plastic, quite uniform silt from Alaska.
2. Hart Brothers sand, a bank-run sand from Massachusetts.
3. Manchester fine sand, a uniformly graded New Hampshire sand which is also a CRREL stock soil.
4. Sibley till, a very well graded glacial till from Massachusetts.

A grain size analysis for each of these soils is shown in Figure 4.

Figure 5 shows the hydraulic conductivity plotted against the mean pressure head. The mean pressure head (in kPa) can be translated directly to tension (in kPa) for most practical purposes.

Figure 6 contains plots of hydraulic conductivity vs degree of saturation for each soil. The saturation values were determined by

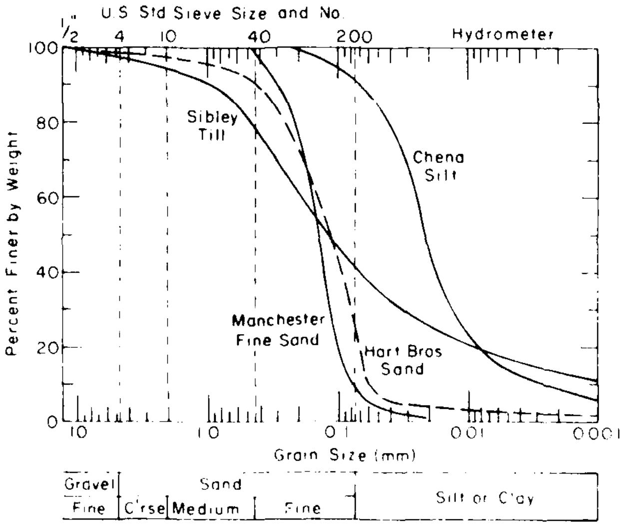


Figure 4. Grain size distribution of four soils.

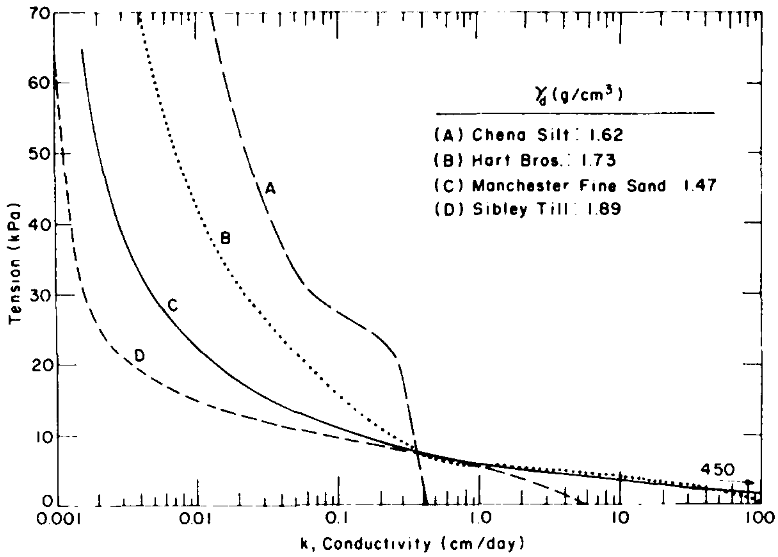


Figure 5. Hydraulic conductivity vs pressure head (tension).

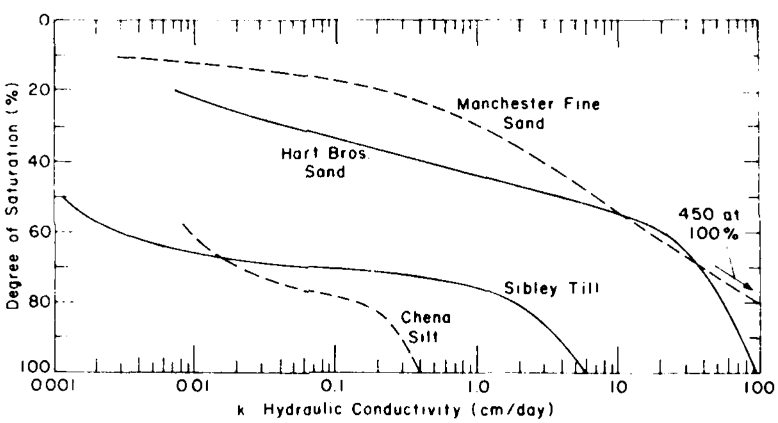


Figure 6. Hydraulic conductivity vs degree of saturation.

translating the moisture contents from the moisture retention curves shown in Figure 7. Data on the moisture retention curves compare results from the unsaturated conductivity cell method explained in this report and the volumetric plate extractor method, previously used for determining moisture retention characteristics.

Soil density has an important effect on both moisture retention and hydraulic conductivity characteristics. Figures 8a and b show this behavior for Chena silt for three densities.

I have not attempted hydraulic conductivity tests above 100 kPa (1 bar) of tension. For such tests, where flow rates would be extremely low, the equipment would require modifications to reduce the amount of moisture loss through cylinder and tubing walls. Tests using the modified equipment are being considered at this time, however.

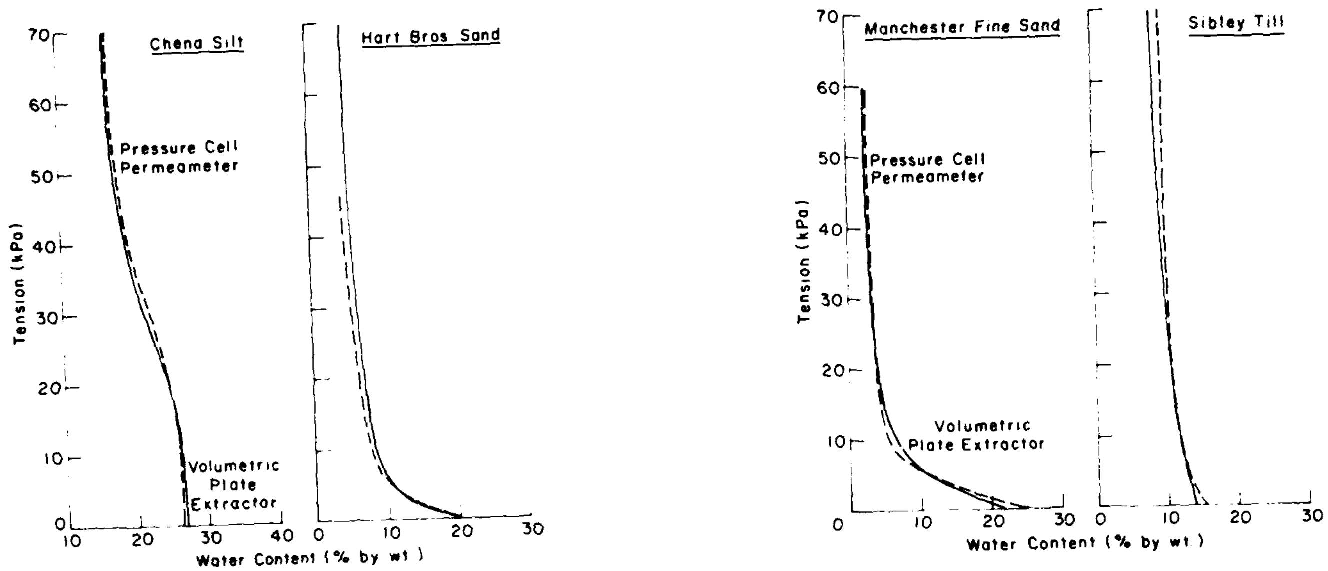


Figure 7. *Comparison of moisture retention results using a volumetric* plate extractor and a pressure cell permeameter.

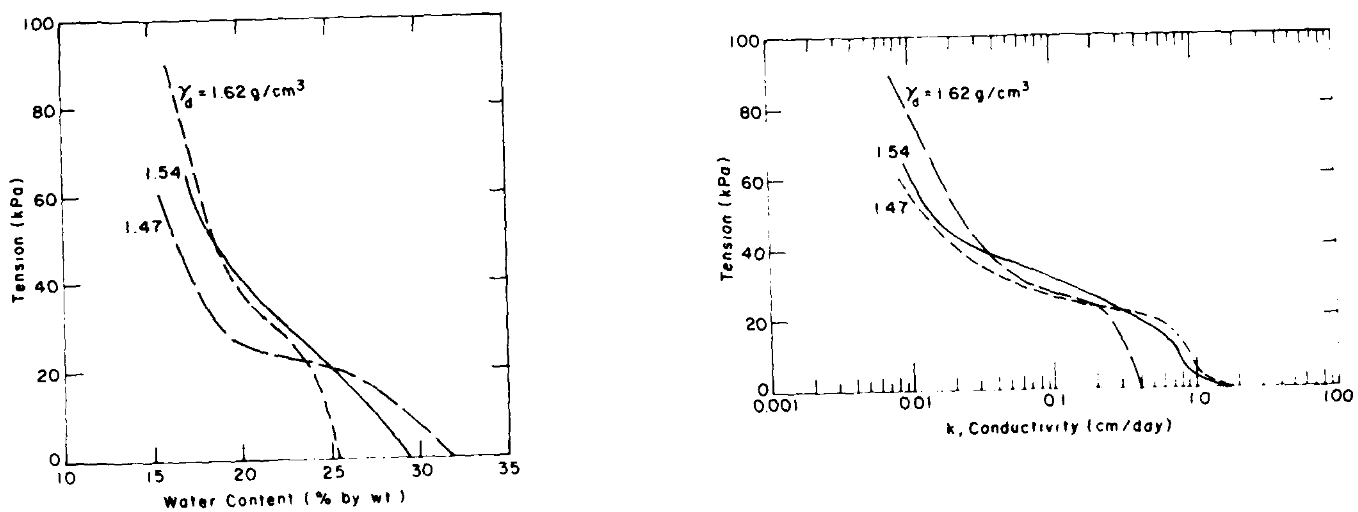


Figure 8. Effect of density on test results for Chena silt.

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